

The Experimental Design and Analysis question in AP Physics 2 sets labs in thermodynamics, circuits, fields, optics and modern physics, but the method never changes: name what you measure, linearize, plot, and say what the slope is.

The Experimental Design and Analysis question

One of the four free-response questions is a lab question. It asks you to design a procedure, say how you would graph the data so the graph is a straight line, and then work with data – plot it, find a slope, and say what the slope tells you. It is not about naming fancy apparatus; it is about what you measure and what you do with the numbers.

Read the question for what is GIVEN and what is to be DETERMINED. The quantity to be determined is almost always the slope (or the intercept) of the graph you are about to design.

Answer every part, even if an earlier part went wrong. The graph and slope parts are marked on what you plotted, not on whether your design matched the reference.

Writing the procedure

Name each quantity you will measure AND the instrument that measures it: ‘a meterstick to measure the height h of the ramp’ earns the point; ‘a meterstick’ does not.

Vary the independent variable over a RANGE – at least five values, spread out. One measurement cannot give a slope.

Say what you hold constant and how. ‘Use the same cart, released from rest from the same mark each time’.

Repeat each trial and average. Say that this reduces RANDOM error; it does nothing for a systematic one.

Remove a specific systematic error by name: zero the force sensor, measure to the center of mass, start timing from a fixed release, use a motion detector instead of a hand-held stopwatch.

Write the steps so someone else could follow them: numbered, in order, with each measurement said once. A paragraph of good intentions loses points that a numbered list keeps.

Linearizing the data

Almost every design question wants a straight-line graph. Start from the equation, put the quantity you control on one side and the one you measure on the other, and match it to $y = mx + b$.

Relationship	Plot y	against x	Slope
$a = g \sin \theta$	a	$\sin \theta$	g
$T = 2\pi\sqrt{L/g}$	T^2	L	$4\pi^2/g$
$T = 2\pi\sqrt{m/k}$	T^2	m	$4\pi^2/k$
$v^2 = 2gh$	v^2	h	$2g$
$F = kq_1q_2/r^2$	F	$1/r^2$	kq_1q_2
$1/s_o + 1/s_i = 1/f$	$1/s_i$	$1/s_o$	-1 (intercept $1/f$)
$V = V_0e^{-t/RC}$	$\ln V$	t	$-1/RC$

Write down what the slope equals, in symbols, BEFORE you take data. That sentence is usually a point on its own.

Units of the slope are the y-unit over the x-unit. For T^2 against L that is s^2/m – and checking it against $4\pi^2/g$ (units s^2/m) is a quick way to catch a wrong plot.

A constant you multiply by does not stop a line being straight; a power or a square root does. If the equation has one, plot that power.

The graph and its slope

Label both axes with the quantity and its unit, and pick scales that spread the data over most of the grid.

Plot the points; do not connect the dots. Draw ONE straight best-fit line with points scattered on both sides.

Find the slope from two points ON THE LINE, far apart, and show the calculation. Two data points are not the line unless the line happens to pass through them.

Say what the slope means and calculate the quantity from it, with units: ‘slope = $4\pi^2/g$, so $g = 4\pi^2/\text{slope} = 9.7 \text{ m/s}^2$ ’.

If the theory says the line passes through the origin and yours does not, the intercept points to a systematic error. Name a plausible one: friction, a reaction time, a zero offset, the mass of a hanger left out.

Error and agreement

Percent difference – $|\text{experimental} - \text{accepted}| \div \text{accepted} \times 100\%$. A few percent is good agreement for a school lab

Random error – scatter about the line; reduced by repeating trials and by a best-fit line through many points

Systematic error – shifts every point the same way; it shows up as a wrong slope or an unexpected intercept, and repeating does not remove it

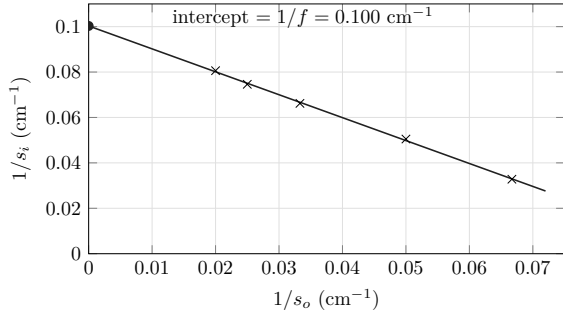
When asked how an error affects the result, push it through the equation and the graph: ‘measuring L to the top of the bob makes every L too short by the bob’s radius; that shifts the line sideways, so it shows in the intercept and leaves the slope – and g – unchanged’. Guessing a direction without the reasoning earns nothing.

‘Human error’ and ‘measure more carefully’ are not sources of error. Name the measurement and what goes wrong with it.

Worked analysis: the focal length of a lens :

A lamp (the object) shines through a converging lens onto a screen. For each object distance s_o , measured with a meterstick, the screen is moved until the image is sharp and the image distance s_i is recorded. Prediction: $1/s_i = -1/s_o + 1/f$, so a graph of $1/s_i$ against $1/s_o$ is a line of slope -1 whose y-intercept is $1/f$.

s_o (cm)	15.0	20.0	30.0	40.0	50.0
s_i (cm)	30.5	19.8	15.1	13.4	12.4
$1/s_o$ (cm ⁻¹)	0.0667	0.0500	0.0333	0.0250	0.0200
$1/s_i$ (cm ⁻¹)	0.0328	0.0505	0.0662	0.0746	0.0806



The best-fit line is extended back to $1/s_o = 0$, where it meets the axis at $1/f$.

- Slope = -1.01 , as the thin-lens equation predicts. Intercept = 0.100 cm^{-1} , so $f = 1 \div 0.100 = 10.0\text{ cm}$.
- Judging when the image is sharpest is the largest random error: the image looks sharp over a few millimetres of screen position. Move the screen in from both sides and take the midpoint, and repeat.
- Measure s_o and s_i from the CENTER of the lens, in its holder; a thick lens measured from its face gives every distance the same offset – a systematic error.
- Labs that keep coming back**
- Gas laws** – a syringe sealed to a pressure sensor at constant temperature: P against $1/V$ is a line of slope nRT . Push slowly, so the gas stays at room temperature
- Resistivity** – $R = V/I$ for different lengths of one wire: R against L/A is a line of slope ρ . Keep the current small so the wire does not warm
- Capacitor charging and discharging** – a voltage sensor across the capacitor; the time to fall to 37% of the starting voltage is RC , and a larger R or C makes it slower
- Field of a long wire** – a magnetic field sensor at distances r from a wire carrying a known current: B against $1/r$ has slope $\mu_0 I/2\pi$. Zero the sensor with the current off, to remove Earth's field
- Refraction** – a ray box and a semicircular block on a protractor: $\sin \theta_1$ against $\sin \theta_2$ (air against glass) has slope n of the glass. Aim at the flat face's center so the ray leaves along a radius, unbent
- Double slit or grating** – a laser through a grating onto a screen at distance L: the spacing of the bright spots against L is a line of slope λ/d , valid while the angles are small
- Planck's constant from LEDs** LED – the voltage at which each LED just lights, V, against the frequency of its light: eV against f has slope h. Judging 'just lights' is the main error; look

through a tube to shut out room light

Fields and circuits – what the design needs

- Draw the circuit, with the ammeter in series and the voltmeter in parallel across the component being studied. A circuit diagram is usually worth a point by itself.
- When a field or force is measured at several distances, measure each distance to the CENTER of the charge, wire or magnet, not to its surface.
- Name the background you remove: Earth's magnetic field, room light, the resistance of the connecting leads. Zero the sensor with the source off, or subtract a reading taken without it.